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COMPARISON BETWEEN ARCTIC AND SUBTROPIC SHIP EXHAUST EFFECTS ON CLOUD PROPERTIES

by

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March, 1992

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Comparison between Arctic and Subtropic Ship Exaust Effects on Cloud Properties

by

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ABSTRACT

Radiative and physical characteristics of subtropic and Arctic shiptracks are compared through the use of AVHRR satellite data and an algorithm developed at the Naval Postgraduate School. Examination of channels 1 and 3 albedos within each region indicate the average subtropic shiptrack brightness is greater than that for Arctic tracks. Arctic shiptracks, however, tend to be brighter than their environment compared to subtropic shiptracks. Subtropic shiptracks tend to be wider and longer than Arctic shiptracks. Due to relatively small sample sizes, additional cases are required to prove statistical significance for channel 3 albedo, channel 3 albedo percent change, width, and length. Increased in-situ measurements are needed for the analysis of conditions necessary and detrimental to the formation of shiptracks.

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I. INTRODUCTION

A. HISTORICAL PERSPECTIVE OF SHIPTRACKS

The 1965 discovery of anomalous cloud lines by TIROS VII, as shown by Conover (1966), led to speculation on the mechanism of cloud line formation. In particular, Conover (1966) made the following conclusions. First, though not definitive, evidence showed the formation of anomalous cloud lines were the result of the stack exhaust of ships. Second, the concentration of condensation nuclei and the number of droplets within the cloud line were much higher than those of the surrounding atmosphere. Third, Conover (1966) discovered anomalous cloud lines could form in clear regions or near areas containing stratus layers. Finally, he concluded inadequate information was available for final proof and recommended additional study.

Conover's initial conclusions resulted in further investigation of anomalous cloud lines and the later discovery and initial analysis of shiptracks. Subsequent examination led to the detection of shiptrails within existing stratocumulus cloud decks. Primary concern during early shiptrack studies centered on two key ingredients: the mechanisms that were responsible for shiptrack formation and the resulting cloud changes. Coakley et al. (1987) concluded the average droplet size within modified shiptrail clouds is smaller than that in the surrounding ambient clouds. Radke et al. (1989) emphasized the importance of high liquid water content and reduced droplet size within shiptracks. Additional studies indicated shiptrack detection occurred primarily at 3.7 micrometers

with little detection possible at visible wavelengths. Thus, while research indicated a tendency for cloud droplet size to decrease within shiptrail clouds, the reasons for such a decrease were not completely understood.

B. AEROSOL SIGNIFICANCE IN CLOUD STUDIES

The importance of aerosol concentration in cloud studies is documented on numerous occasions. Charlson et al. 1987 examined the potential for climate modification by algae-produced sulfate aerosols. Albrecht (1989) discussed the relationship between aerosol concentrations and the fractional cloudiness of marine stratocumulus fair-weather clouds. Likewise, shiptrack studies by Hindman (1990), Coakley et al. (1987) and Porch et al. (1990) all discussed a relationship between shiptrack formation and aerosol concentration. In particular, Porch et al. (1990) discussed the influence ship exhaust heating plays in the cloud formation process. Hindman (1990) suggested shiptrail clouds are triggered by heat, moisture, and momentum, and are sustained by cloud condensation nuclei and momentum.

C. THESIS OBJECTIVE

Arctic and subtropic regions are areas of extreme environmental conditions. In particular, subtropic regions have deeper boundary layers and greater atmospheric moisture than do Arctic regions. Consequently, shiptracks which form in each region are expected to differ in radiative characteristics.

While it is true many studies on subtropic shiptracks have begun to clarify mechanical and cloud modification questions, much has been left unanswered on the characteristics

of high latitude shiptracks. The goal of this thesis is to compare the radiative and physical characteristics of high latitude (above 60 degrees north latitude) shiptracks with those in subtropic regions (below 30 degrees north latitude). In particular, this thesis utilizes a shiptrack detection algorithm which searches for and analyzes shiptracks using data obtained from polar orbiting satellites.

II. THEORY

A. CLOUD PHYSICS

Clouds are composed of water droplets or ice crystals, the size of which are partly dependent on the dimension and concentration of aerosols. Brock (1972) breaks the percentage of aerosol forming mechanisms as 75% for natural and antropogenic sources and 25% for photochemical and other chemical processes. In particular, Brock (1972) further separates aerosol sources as sea spray (40%), wind swept dust (20%), industrial activities (5%), and the conversion of atmospheric gases to smaller particles (25%).

On the average, clouds cover approximately half the earth. Aerosols, which are present in all cloud types, play a major role in determining the radiation budget of the earth, moderating the earth's climate, and contaminating radiometric observations necessary for sounding the atmosphere and remotely sensing surface parameters (Kidder and Vonder Haar, 1991). The existence of aerosols alone, however, does not guarantee cloud formation.

Aerosols must exist in sufficient quantity and size to serve as cloud condensation nuclei (CCN). Typical aerosol sizes range from a radius of .001 micrometers for ionic sized particles to greater than 10 micrometers for the larger salt, dust, and combustion particles (Brock, 1972). The radius of a typical CCN is on the order of 0.01 micrometers. Cloud droplets form when the atmosphere becomes supersaturated with respect to water. The number of cloud droplets which form is dependent on the cloud condensation nuclei concentration and the rate at which the air

cools and saturates. Twomey and Warner (1967) successfully correlated the relationship between cloud condensation nuclei concentration and the number of cloud droplets. They concluded an increase in the number of CCN results in an increase in cloud droplet concentration. Other studies by Charlson et al. (1987) and Radke et al. (1989) indicated an increase in cloud droplet concentration as the number of cloud condensation nuclei increase.

B. WAVELENGTHS USED

Recently, several investigators have used satellite data to infer cloud properties of shiptracks (Coakley, et al., 1987). The instrument used or the measurement of cloud radiance data is the AVHRR (Advanced Very High Resolution Radiometer) located on board the NOAA polar orbiting satellites. The AVHRR is equipped with 5 channels (1 through 5) but only channels 1, 3, and 4 are pertinent for shiptrack analysis.

Channel 1 is located in the visible portion of the light spectrum with a wavelength range from .58 to .68 micrometers. Here, a photon interacting with a cloud will be scattered, reflected or transmitted through the cloud. In this case, the complex part of infrared index of refraction, which determines the ability of cloud droplets to absorb incoming radiation, is very small. Consequently, in this portion of the spectrum, incoming radiation is not absorbed. Cloud reflectance is a function liquid water content, cloud thickness and droplet size.

Channel 3 is located in the near infrared region of the spectrum. It utilizes a wavelength range from 3.55 to 3.93 micrometers. The range center of 3.7 micrometers represents the wavelength where shiptracks are most detectable. At this wavelength, a

photon entering a cloud will be absorbed, scattered, or reflected but not transmitted. In this case, the complex index of refraction increases by a factor of ten thousand compared to visible wavelengths. Consequently, absorption is significant and cloud reflection is a function of droplet size only (Mineart, 1988).

Channel 4 is located in the infrared portion of the light spectrum and utilizes the wavelength range from 10.3 to 11.3 micrometers. Channel 4 is unique in that it is a function of thermal emission only. The independence of channel 4 from solar effects presents the opportunity to examine cloud top temperatures. Thus, channel 4 is useful in cloud temperature analysis.

The ability of the AVHRR to measure cloud reflectance makes it a critical tool in the detection and analysis of shiptracks. Because shiptracks tend to be brighter than their environment, the AVHRR is useful in distinguishing between shiptrack reflectance and neighboring cloud reflectance.

III. METHODOLOGY

A. DATA ASSIMILATION

1. Shiptrack Satellite Data Sources

Shiptrack satellite data was gathered from two sources. Arctic satellite data was obtained from satellite tape archives located at the Naval Oceanographic and Atmospheric Research Laboratory (NOARL). Subtropic satellite data was obtained from the Naval Postgraduate School Air-Ocean Interactive Digital Environmental Analysis (IDEA) Lab. In particular, each subtropic shiptrack was obtained from tapes produced during the 1987 First ICSSP Regional Experiment (FIRE).

2. Shiptrack Locations

The choice of location for Arctic shiptrack analysis was based primarily upon two factors. First, the prospective increase in Arctic naval activity in the vicinity of Greenland northeast into the Barents Sea increases the necessity to increase knowledge on Arctic operations. This, coupled with the continued presence of the new Russian Federation Fleet, prompts the decision to concentrate high latitude shiptrack studies in the vicinity of the GIUK gap northeast into the Barents Sea. Second, the increased concentration of shipping in the vicinity of the GIUK Gap presents a higher potential for the detection and analysis of high latitude shiptracks.

B. REMOTE SENSING UTILIZATION

1. Importance

The inability to directly measure radiative properties within the atmosphere requires the use of satellite remote sensing. In particular, the lack of in-situ shiptrack data within Arctic regions places the burden for initial study entirely within the capabilities of current satellite technology. Thus, satellite technology is critical for the detection of shiptracks needs.

2. Satellite Used

The satellites used in the detection of shiptracks were the NOAA polar orbiting series. All satellite data was obtained during late spring to early summer. In particular, all Arctic shiptrack data was obtained from NOAA 11 between the dates 02 June and August 21 1989. The focus on shiptracks within the vicinity of the GIUK Gap eastward into the Greenland and Barents Seas restricted the availability of data both in shiptrack number and timeframe. Consequently, all Arctic shiptrack data was confined to the dates mentioned. Subtropic data was obtained from NOAA 9 and NOAA 10 from 01 July to 13 July 1987. While the amount of subtropic shiptrack data was readily available, the number of cases examined was restricted to be consistent with the Arctic cases studied. The satellites, dates, times, and region analyzed are summarized in Table 1.

As indicated earlier, the sensor employed for the detection of shiptracks in both the Arctic and subtropic regions is the Advanced Very High Resolution Radiometer

(channels 1, 3, 4). In particular, this sensor is a scanning radiometer which makes calibrated measurements of upwelling radiation from small scan spots or pixels that are scanned across the satellite track. Both channels 1 and 3 measure radiance as a function of geometric dependence. Furthermore, each calculation gives an indication of hemispheric vice localized reflectance. Channel 1 estimates cloud radiance by linearly scaling measured reflectance values into albedo pixel values. Channel 3 radiance consists of thermal emission and reflected energy but the thermal emission portion is removed for cloud temperature analysis by channel 4. Table 2 summarizes the available and shiptrack pertinent channels on the AVHRR.

TABLE 1
SHIPTRACK DETECTION SATELLITES

Satellite	Region	Scan Date	Scan Time
NOAA 11	Arctic	02 June 1989	0929 UTC
NOAA 11	Arctic	17 June 1989	1014 UTC
NOAA 11	Arctic	25 June 1989	1035 UTC
NOAA 11	Arctic	27 June 1989	1335 UTC
NOAA 11	Arctic	30 June 1989	1447 UTC
NOAA 11	Arctic	04 July 1989	1221 UTC
NOAA 11	Arctic	05 August 1989	1013 UTC
NOAA 11	Arctic	07 August 1989	0952 UTC
NOAA 11	Arctic	21 August 1989	1410 UTC
NOAA 9	Subtropic	01 July 1987	2303 UTC
NOAA 10	Subtropic	03 July 1987	1626 UTC
NOAA 9	Subtropic	13 July 1987	2314 UTC

TABLE 2 AVHRR AND PERTINENT SHIPTRACK CHANNELS				
AVHRR Channel	**Type**	**Wavebands (micrometers)**	**Center Frequency (micrometers)**	**Used for Shiptrack Detection**
1	Visible	.58 - .68	.63	YES
2	Visible	.73 - 1.10	0.83	NO
3	Near-Infrared	3.55 - 3.93	3.7	YES
4	Infrared	10.30 - 11.30	11	YES
5	Infrared	11.50 - 12.50	12	NO

C. NPS DEVELOPED SHIPTRACK ALGORITHM

1. Purpose

Figure 1 depicts the NPS shiptrack algorithm, developed by Kurt Nielsen. Utilizing the approaches of Coakley et al. (1987) and Morehead (1988), this algorithm is designed to detect the presence of shiptracks and generate average values of channels 1 and 3 albedo and channel 4 temperature for each shiptrack. Additionally, the algorithm is devised to approximate shiptrack length, width, and the average albedo percent change between each shiptrack and its surrounding environment. In this situation, a shiptrack average value represents the average of three pixel values located within the center of the shiptrack. Similarly, an average environmental value represents the average of three pixels located on either side of the shiptrack. The separation distance between each environmental pixel average and the shiptrack boundaries is 15 pixels.

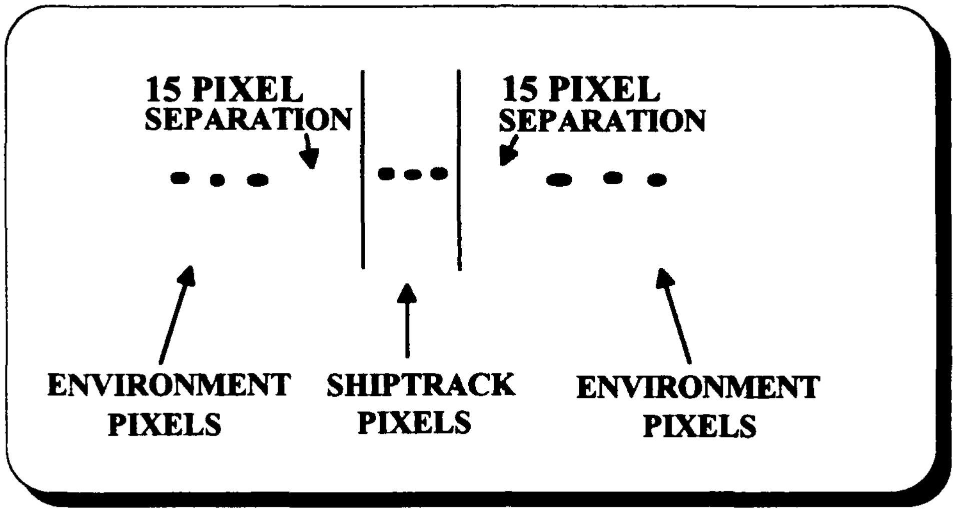

Fig. 1. Shiptrack Average Value Location: depicts the location of shiptrack and environment average pixel values

2. Components

The algorithm is composed of three "subprograms." The first, called "findthem", determines potential shiptrack segment locations. The second subprogram, "findnext", generates two shiptrack data files. The final subprogram, known as "extsamp3", rewrites both shiptrack data files into tabular format for importation into a graphics-producing program (LOTUS 1-2-3).

3. Operation

Operation of the algorithm requires the input of a raw 512 x 512 channel 3 subscene. The subscene is scanned by the "findthem" subprogram for potential shiptrack "brightness neighborhoods." In doing so, the algorithm compares each pixel value with a neighboring pixel value. If a marked difference between pixels is

determined to exist, the brighter pixel is labeled a neighborhood. Subsequent brightness neighborhoods which exhibit a similar increase in brightness level are linearly connected. Connected segments are considered potential shiptrack locations. A final comparison between connected segments and the raw channel three image allows two checks to occur. First, it allows a comparison between the algorithm-determined shiptrack segment and the actual shiptrack to determine the amount of shiptrack detected. Second, it assists in the filtering of segments misidentified as shiptrack segments. Figure 2 illustrates the generation of shiptrack neighborhoods and potential shiptrack segments.

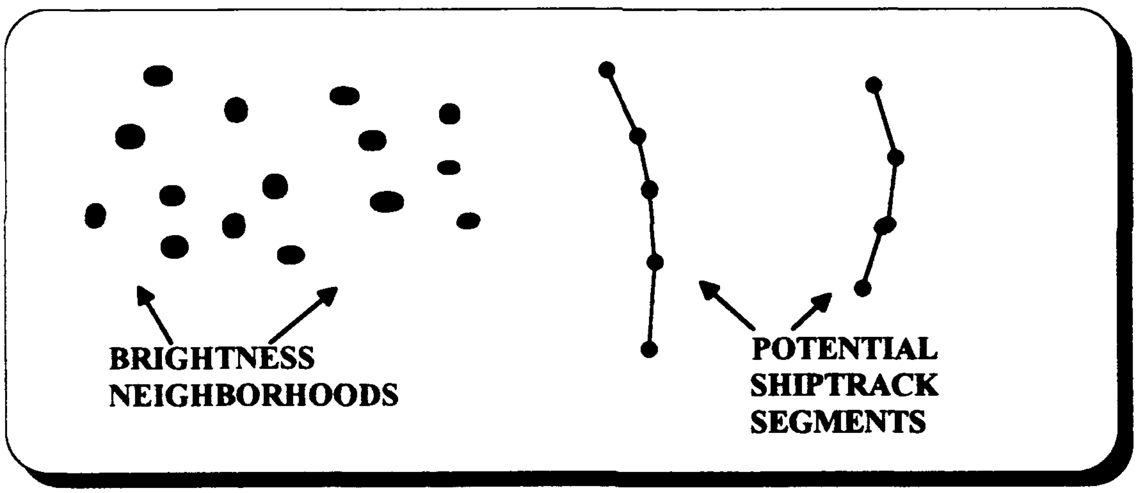

Fig. 2. Brightness Neighborhoods / Shiptrack Segments: indicates difference between distinct brightness neighborhoods and potential shiptrack segments (linearly connected brightness neighborhoods)

After the identification and verification of shiptrack segments is complete, the subprogram "findnext" scans the channels one, three, and four images and extracts

shiptrack data. This data is placed into two files and, based upon the previous comparison between the raw channel three image and the shiptrack brightness neighborhood data, are purged of data misidentified as shiptrack segments. The final subprogram, "extsamp3", converts the remaining data, now consisting entirely of shiptrack segments, into two files for the graphics-producing software package LOTUS 1-2-3.

IV. RESULTS

A. SHIPTRACK LOCATION

1. Arctic

Nine Arctic shiptrack examples are examined. All shiptracks are located in the region between western Greenland eastward into the Greenland, Barents, and Kara Seas. In particular, all Arctic shiptracks are located between 68 and 80 degrees north latitude. Figure 3 gives the location for Arctic shiptracks. Figures 4 through 12 represent a channel three image for each Arctic case analyzed. The specific location of each track is summarized in Table 3.

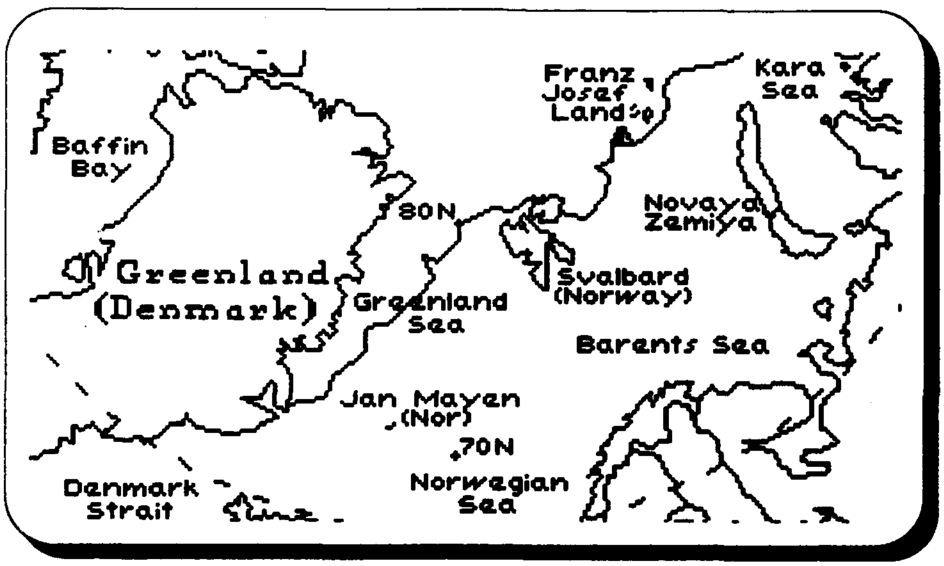

Fig. 3. Arctic Shiptrack Regional Location: dashed line indicates Arctic Circle; line east of Greenland is ice zone

TABLE 3 ARCTIC SHIPTRACK LOCATION	
ARCTIC CASE	**LOCATION**
1	WEST COAST OF GREENLAND (BAFFIN BAY)
2	WEST COAST OF GREENLAND (BAFFIN BAY)
3	WEST COAST OF GREENLAND (BAFFIN BAY)
4	WEST COAST OF NOVAYA ZEMLYA (KARA SEA)
5	EAST COAST OF NOVAYA ZEMLYA (KARA SEA)
6	NORTHEAST OF GREENLAND (GREENLAND SEA)
7	EAST OF GREENLAND (BARENTS SEA)
8	WEST OF SPITZBERGEN (GREENLAND SEA)
9	NORTHWEST OF SVALBARD (GREENLAND SEA)

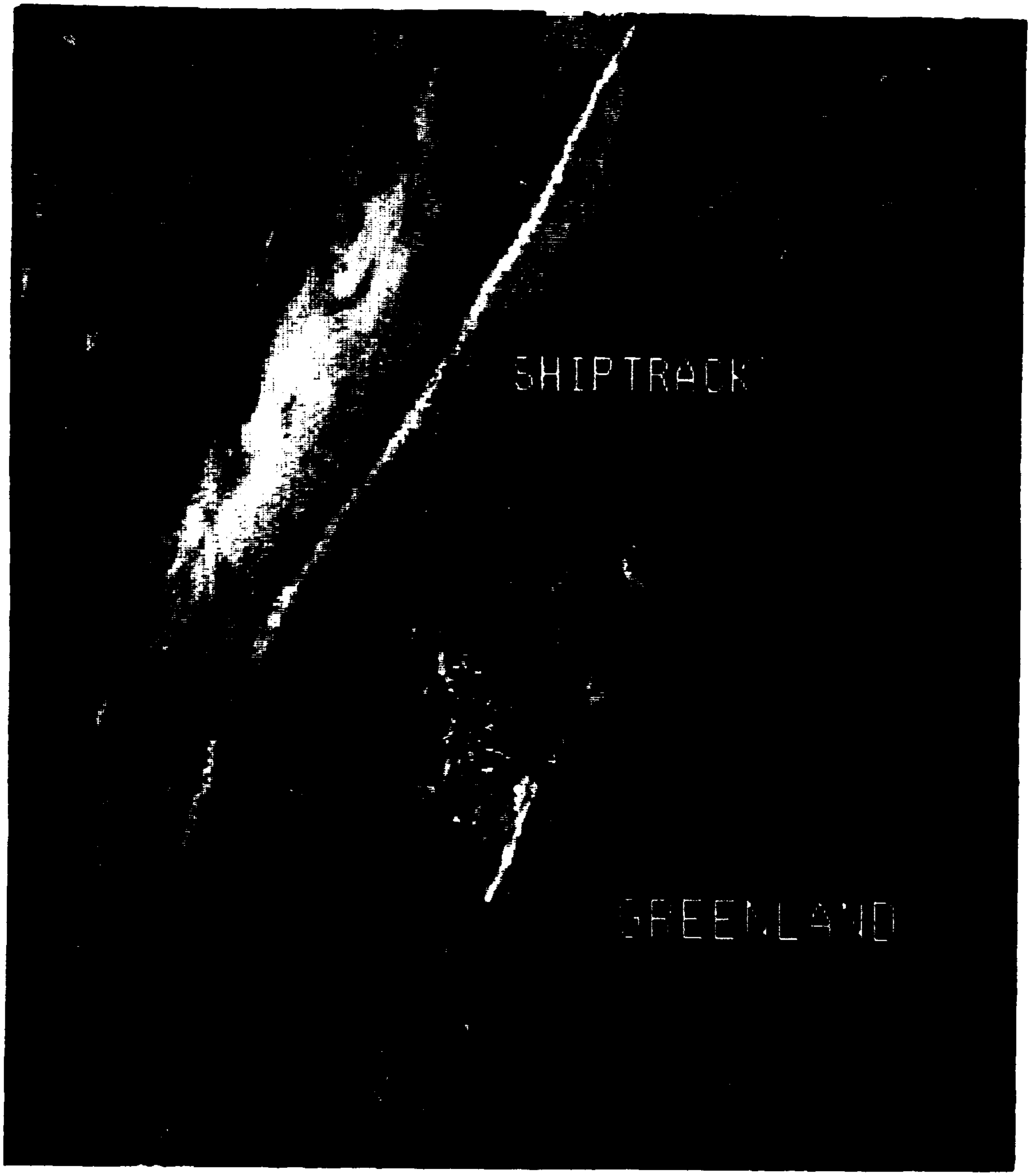

Fig. 4. Arctic Shiptrack Case 1: 21 August 1989 1410 UTC

Fig. 5. Arctic Shiptrack Case 2: 27 June 1989 1335 UTC

Fig. 6. Arctic Shiptrack Case 3: 30 June 1989 1447 UTC

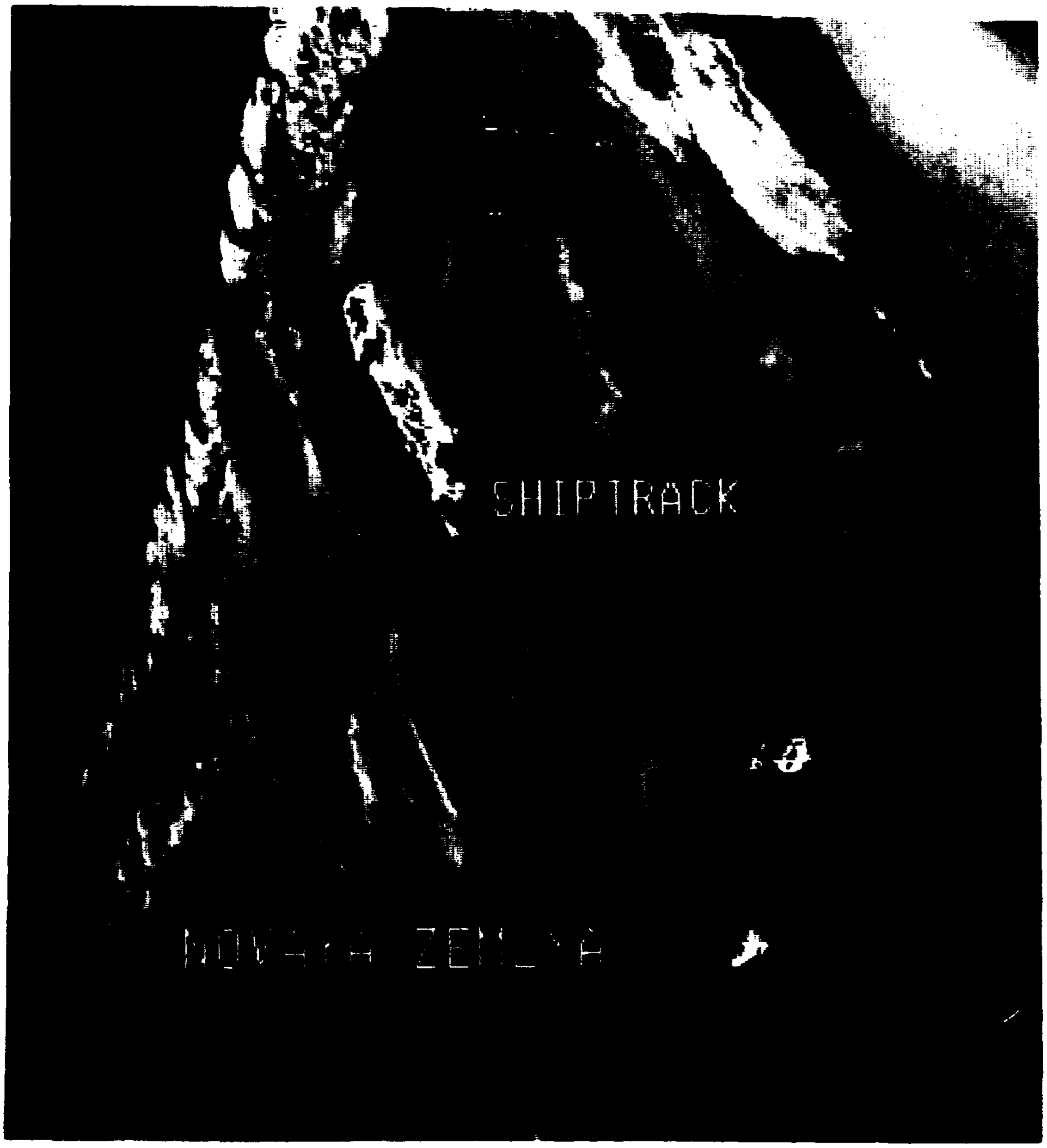

Fig. 7. Arctic Shiptrack Case 4: 05 August 1989 1013 UTC

Fig. 8. Arctic Shiptrack Case 5: 07 August 1989 0952 UTC

Fig. 9. Arctic Shiptrack Case 6: 04 July 1989 1221 UTC

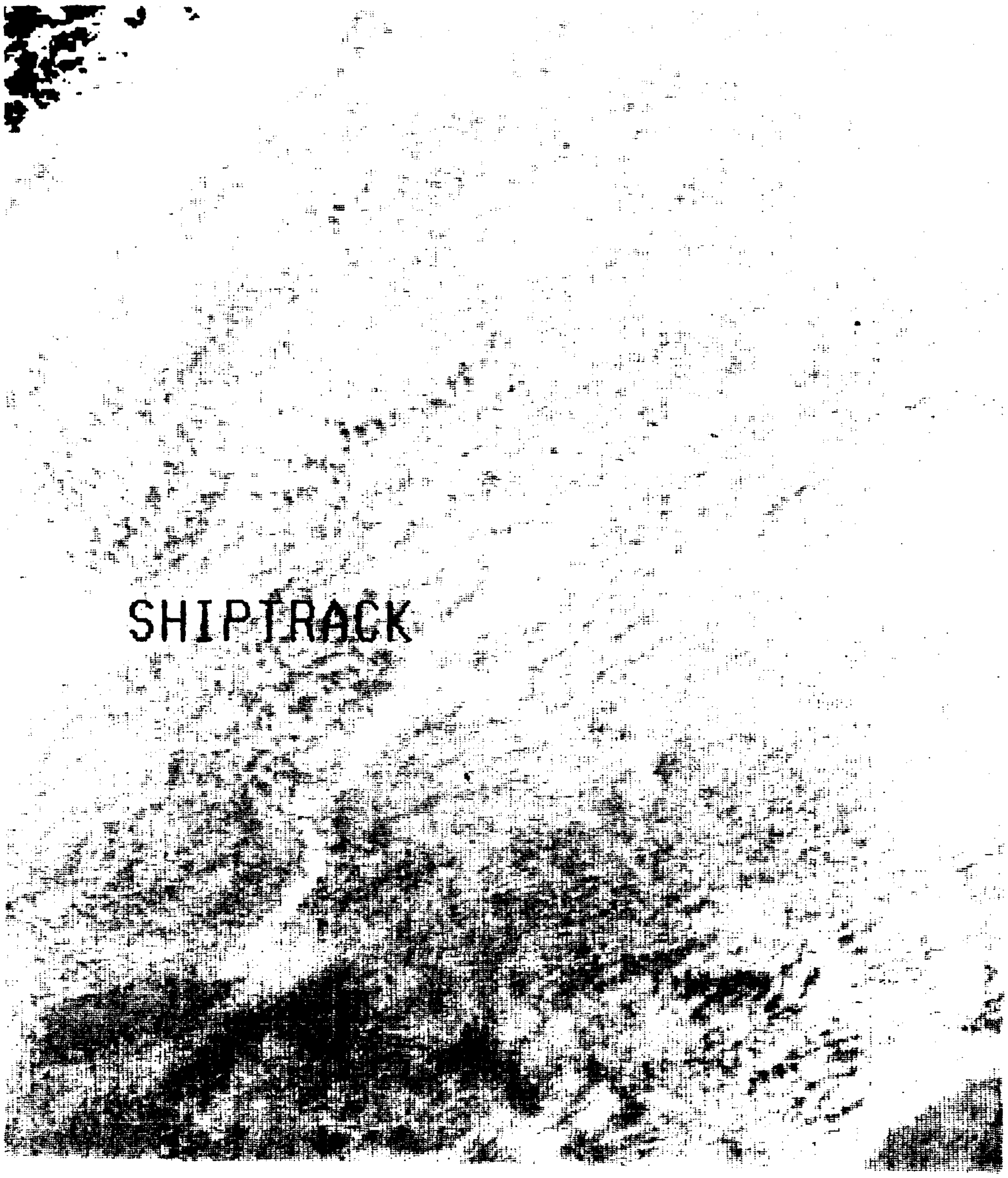

Fig. 10. Arctic Shiptrack Case 7: 25 June 1989 1035 UTC

Fig. 11. Arctic Shiptrack Case 8: 17 June 1989 1014 UTC

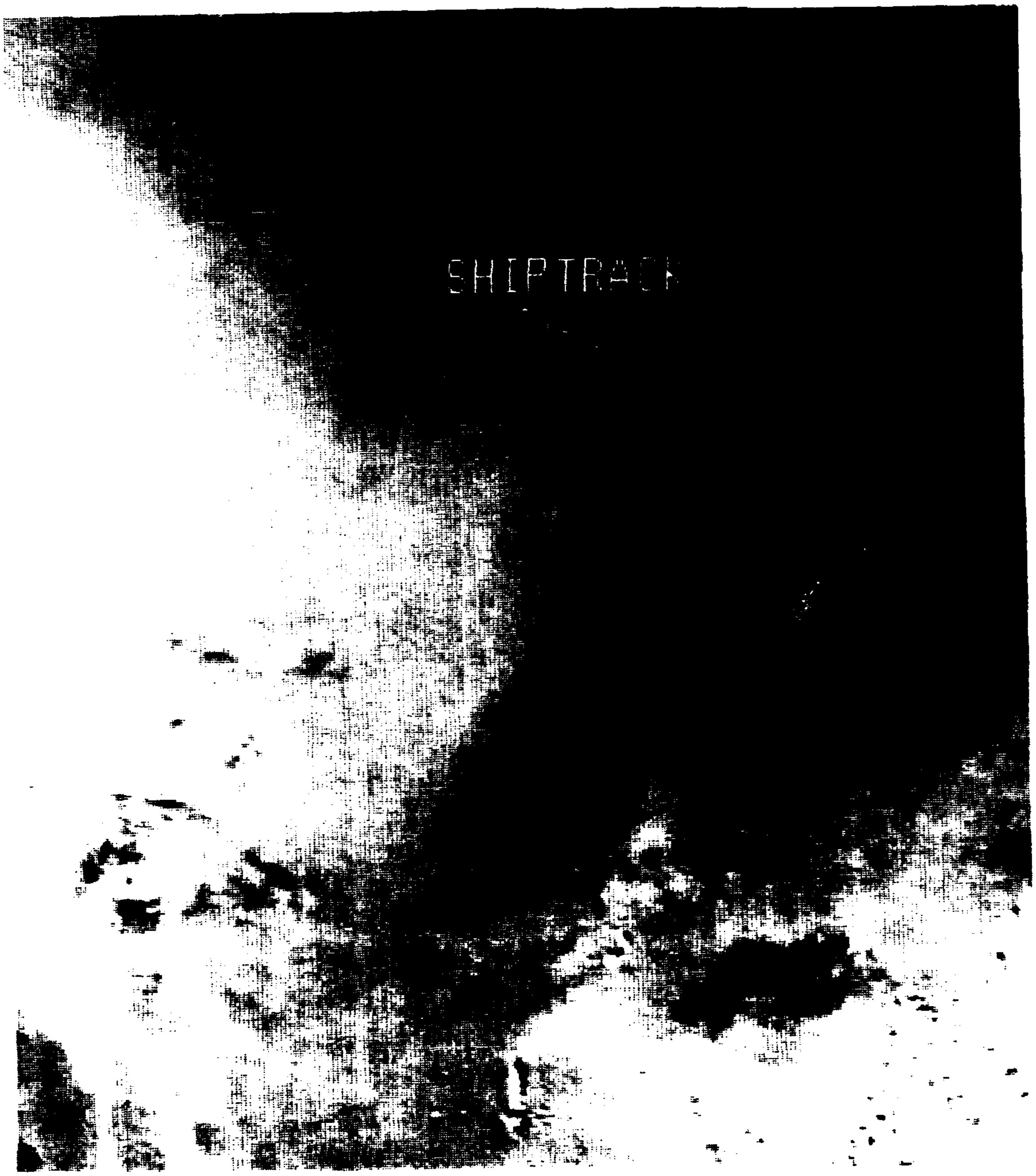

Fig. 12. Arctic Shiptrack Case 9: 02 June 1989 0929 UTC

2. Subtropic

Ten subtropic shiptrack cases are analyzed. All cases are located in the Pacific Ocean west of Baja, California. In particular, all subtropic shiptracks are located between 20 and 30 degrees north latitude. Figure 13 describes the subtropic shiptrack analysis region. Figures 14 through 18 represent channel three images of each subtropic shiptrack analyzed.

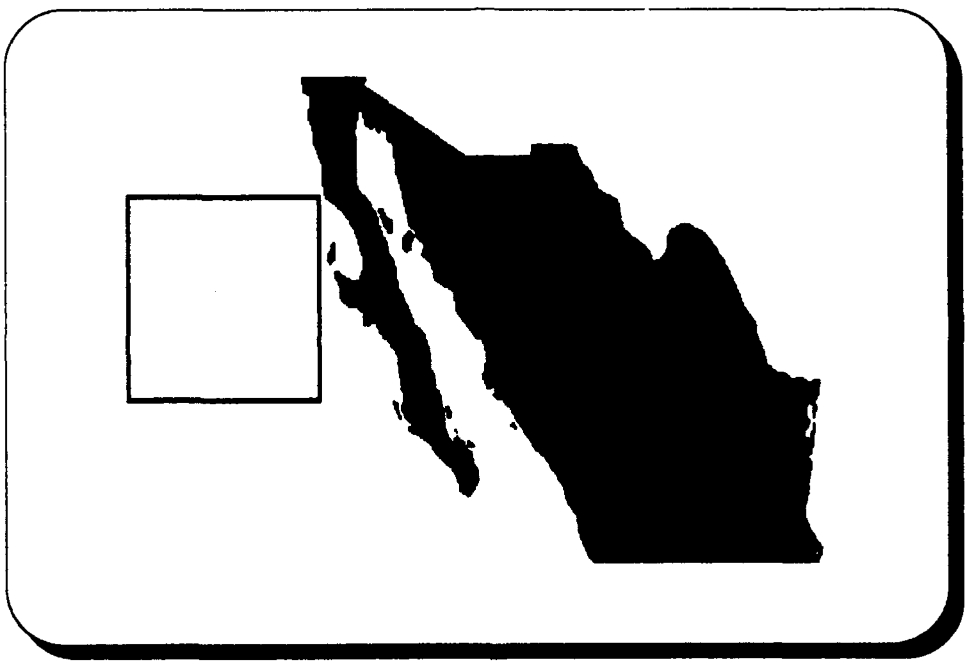

Fig. 13. Subtropic Shiptrack Region: box represents shiptrack analysis area

Fig. 14. Subtropic Shiptrack Cases 1 and 2: 13 July 1987 2314 UTC; Case 1 on left; Case 2 on right

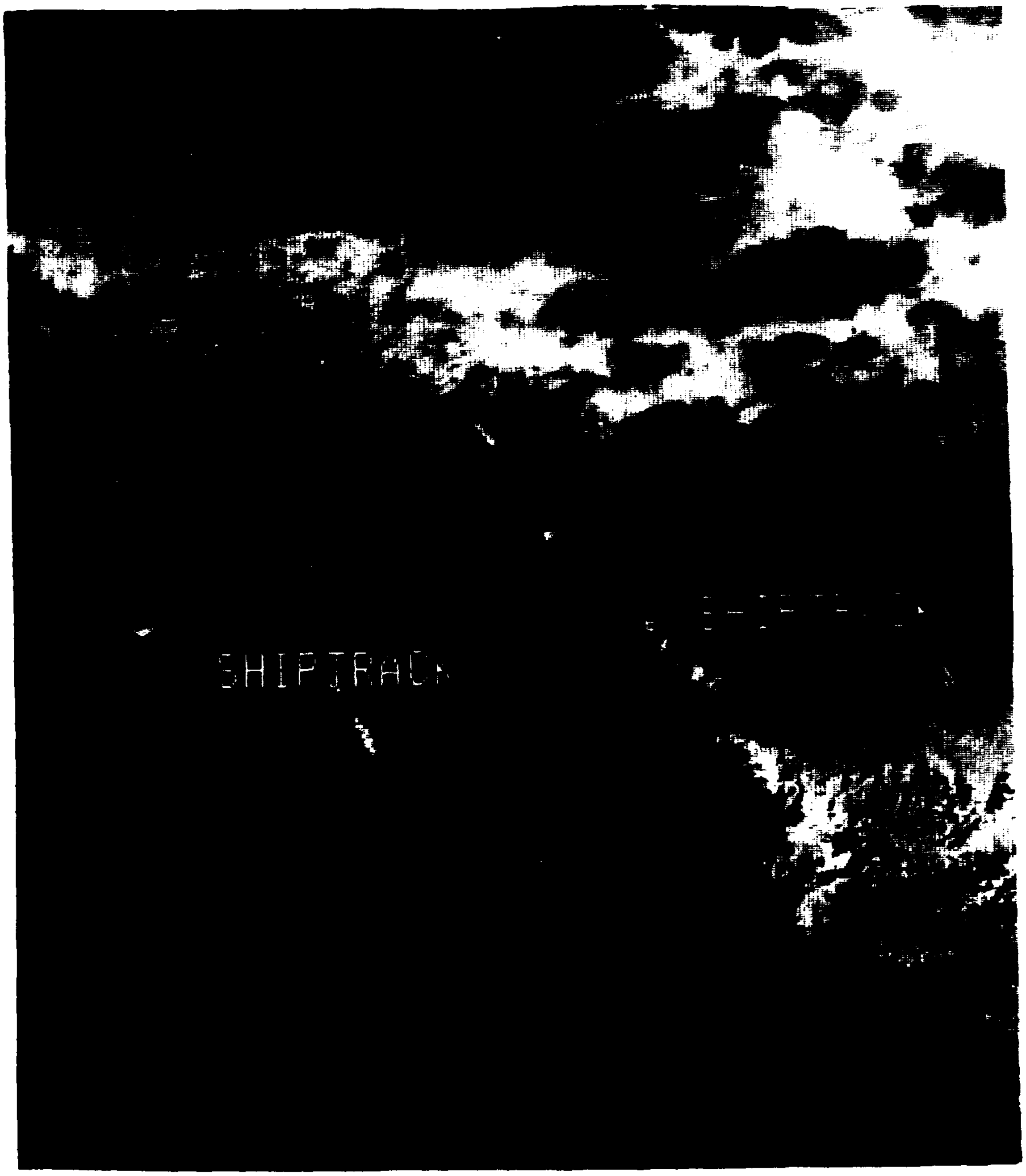

Fig. 15. Subtropic Shiptrack Cases 3 and 4: 13 July 1987 2314 UTC; Case 3 on right; Case 4 on left

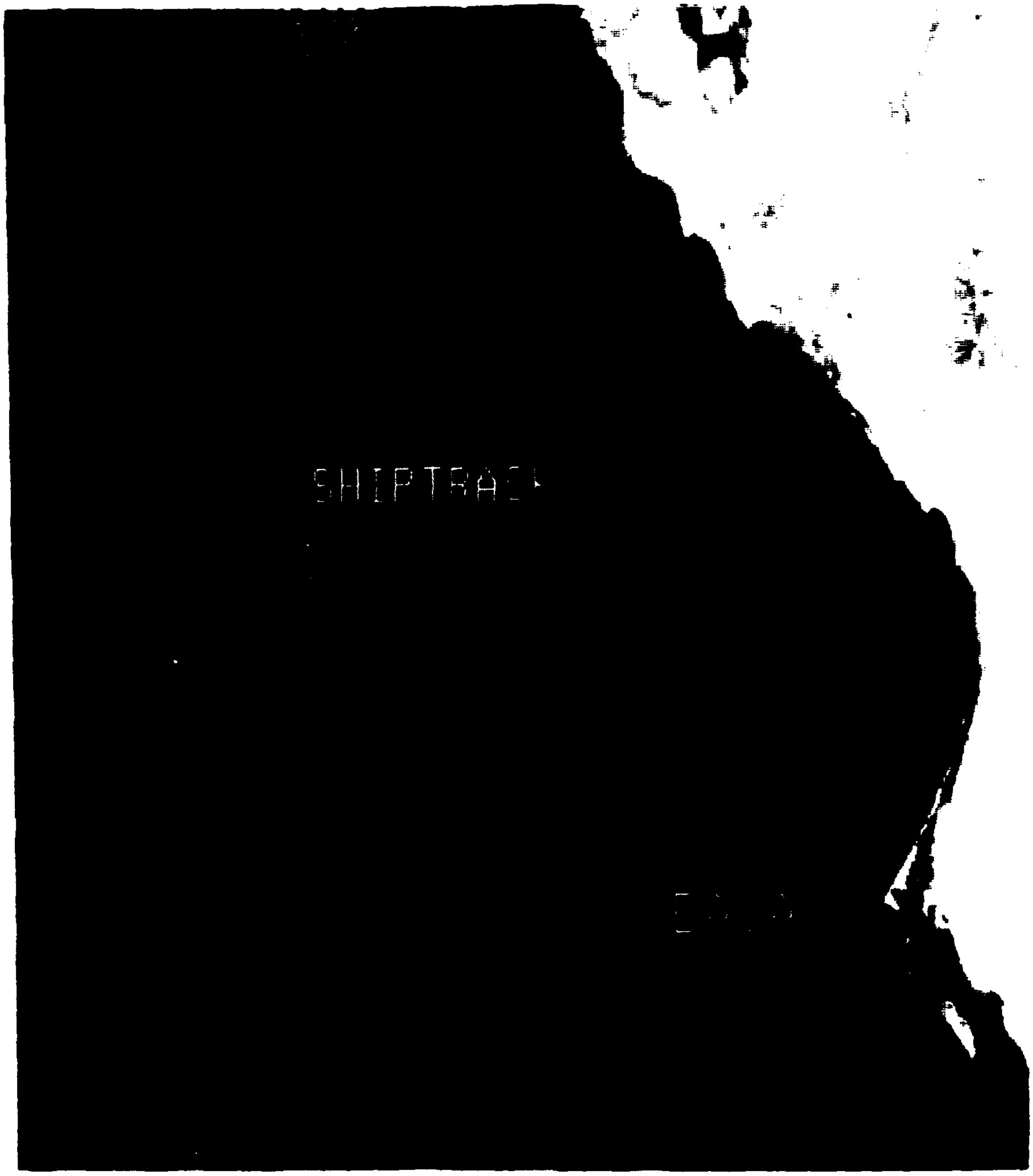

Fig. 16. Subtropic Shiptrack Case 5: 01 July 1987 2203 UTC

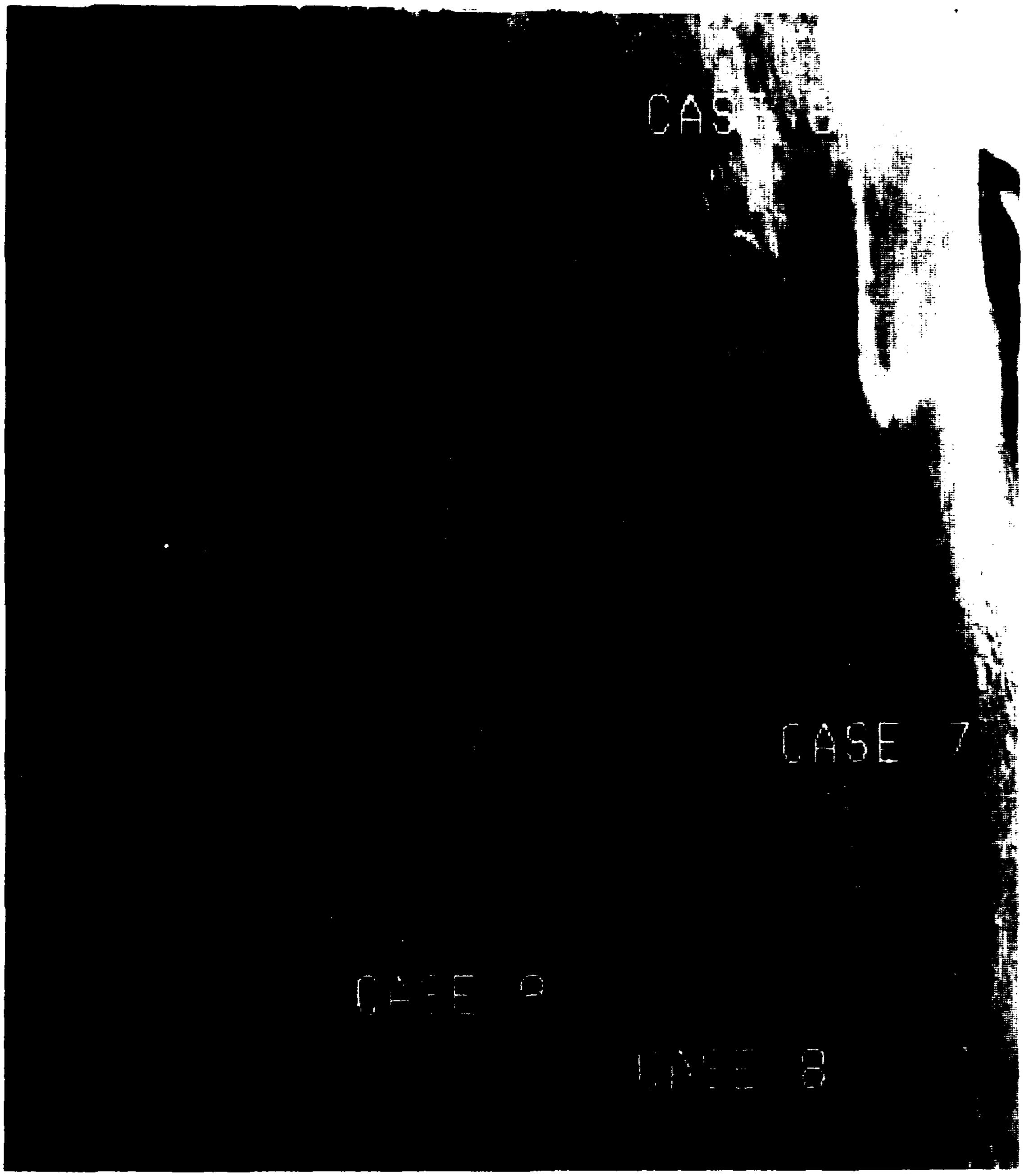

Fig. 17. Subtropic Shiptrack Cases 6 through 9: 03 July 1987 1626 UTC

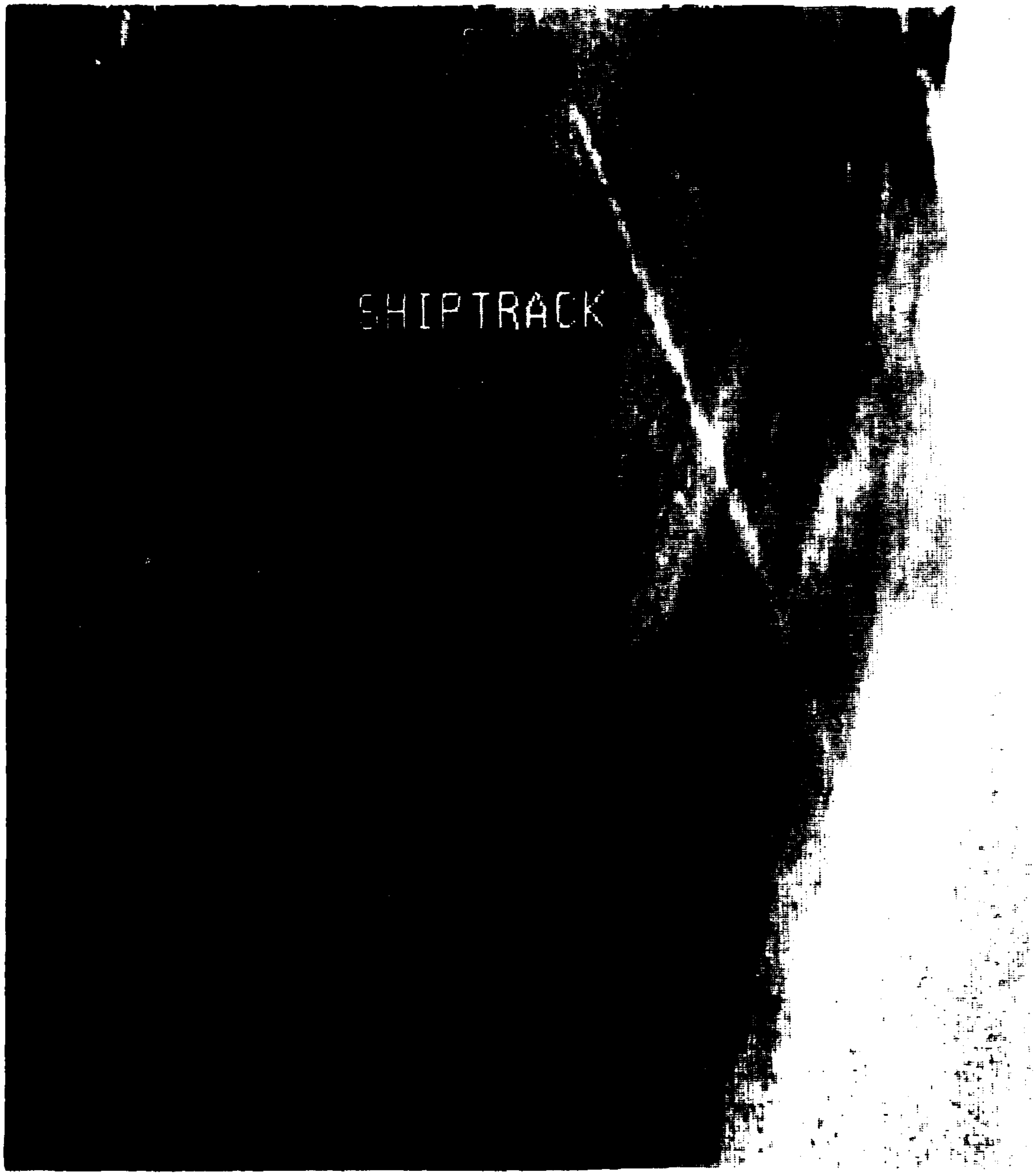

Fig. 18. Subtropic Shiptrack Case 10: 03 July 1987 1626 UTC

B. RAW DATA

Figures 19 through 23 present sample profiles of radiative data plotted by the algorithm for Arctic shiptrack Case 1 (21 August 1989 1410 UTC). A comparison between Figures 19 and 20, which show channels 1 and 3 albedo, indicate similarities in albedo characteristics. In particular, both figures indicate channels 1 and 3 albedos decrease in areas where cloud cover is relatively thin or nonexistent. Furthermore, decreases in albedo coincide with temperature increases indicated in Figure 21. Noteworthy are the albedo minimums and temperature maximums at the 11 and 135 km track points which coincide with cloud gaps in Figure 4. All cases studied indicate similar trends in areas deficient in clouds.

Figures 22 and 23 show channels 1 and 3 albedo percent changes. Figure 22 indicates a marked decrease in channel 1 albedo percent change in regions containing little or no cloud cover. Figure 23 similarly indicates the same trend for channel 3 albedo percent change but not at the same degree as channel 1. All cases studied exhibit similar trends.

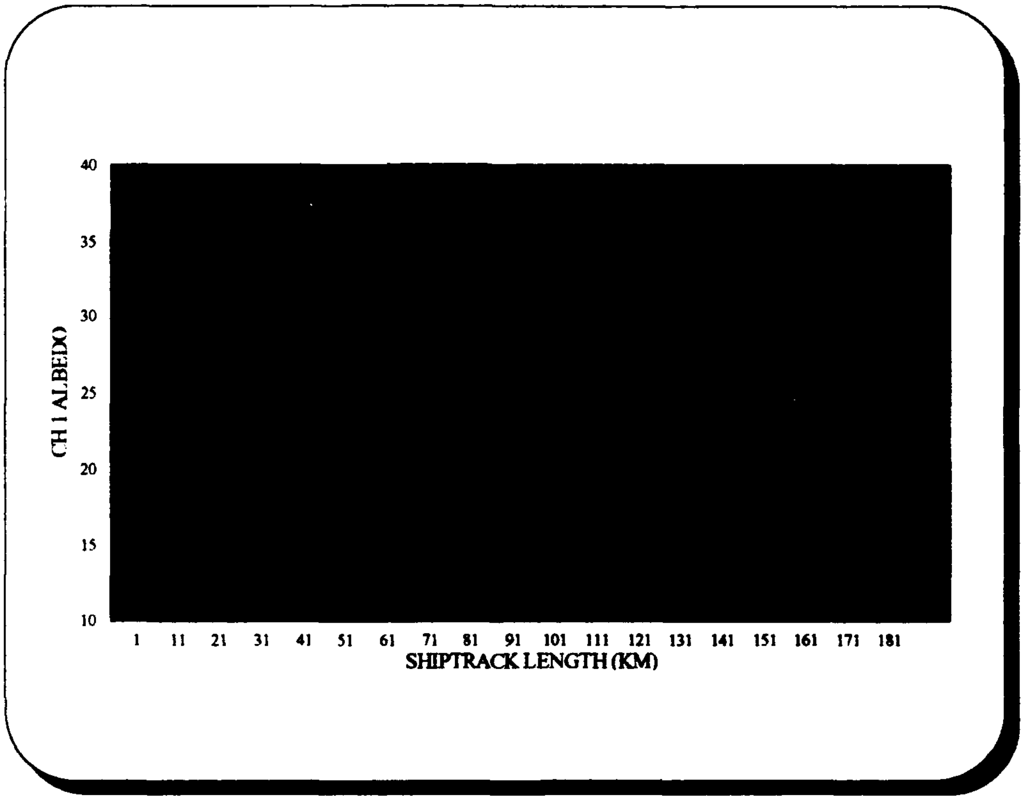

Fig. 19. Shiptrack Algorithm Raw Data Plot: represents Arctic Shiptrack Case 1 Channel 1 Albedo; 1 indicates head of shiptrack

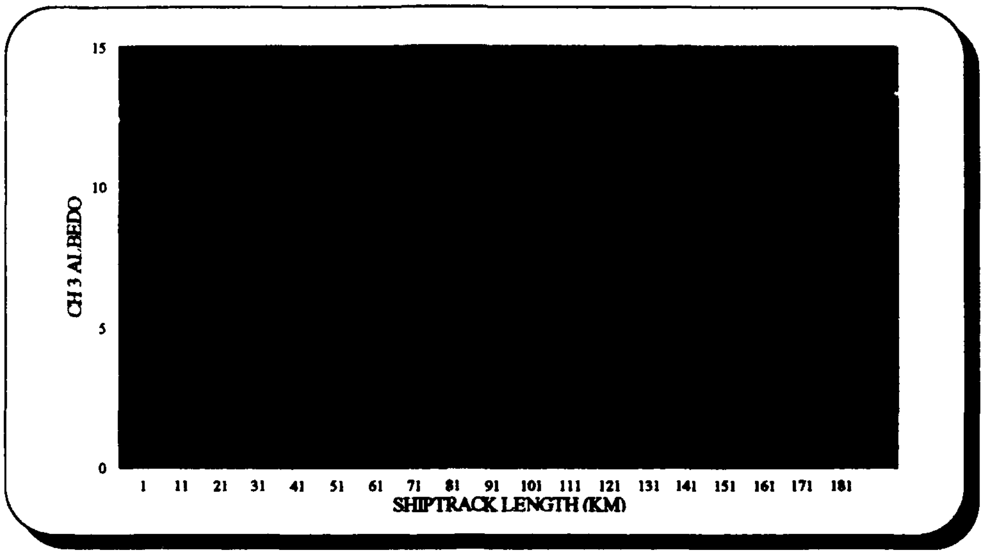

Fig 20. Shiptrack Algorithm Raw Data Plot: represents Arctic Shiptrack Case 1 Channel 3 Albedo; 1 indicates head of shiptrack

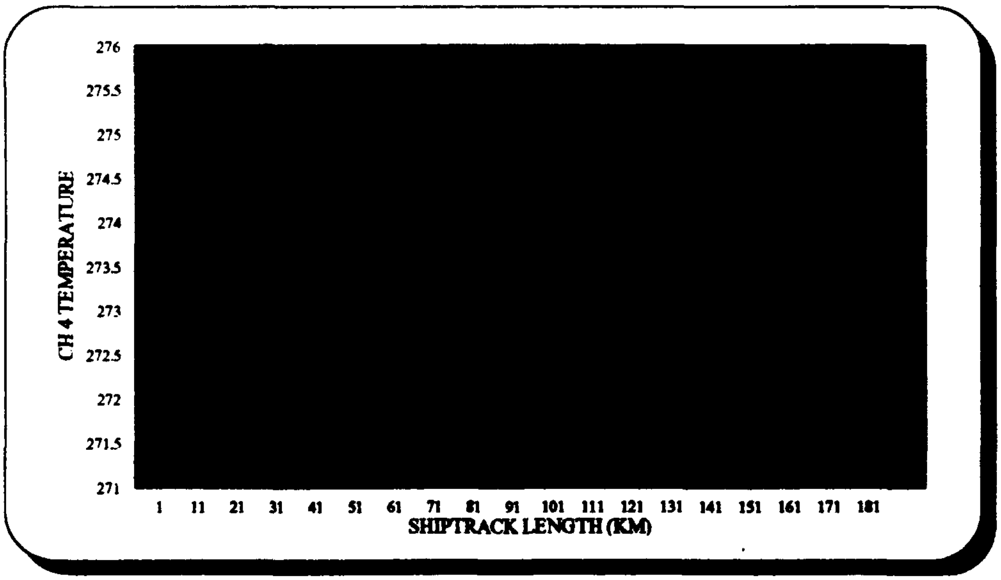

Fig 21. Shiptrack Algorithm Raw Data Plot: represents Arctic Shiptrack Case 1 Channel 4 Temperature; 1 indicates head of shiptrack

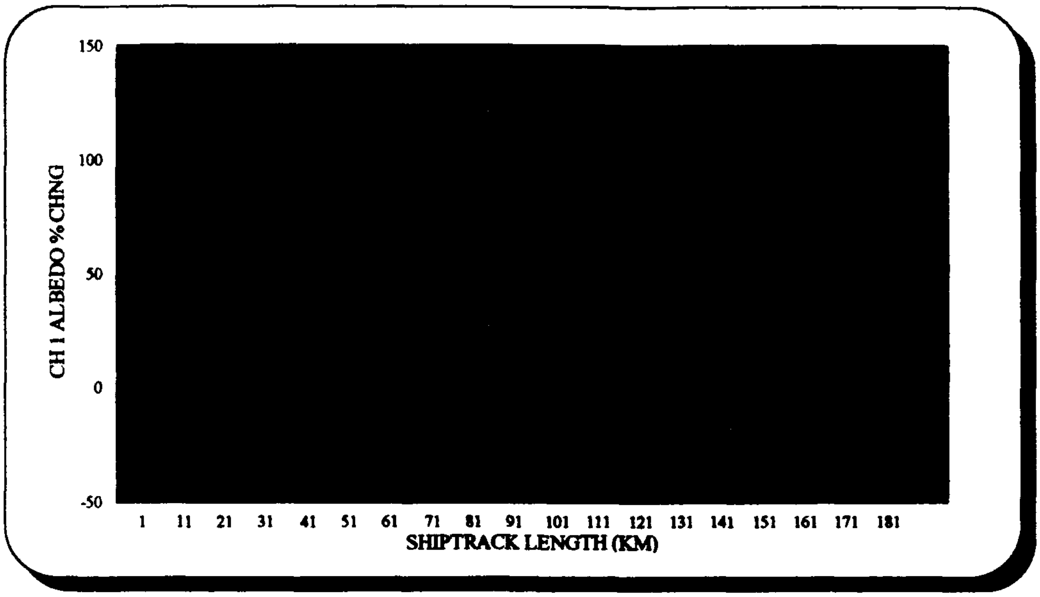

Fig 22. Shiptrack Algorithm Raw Data Plot: represents Arctic Shiptrack Case 1 Channel 1 Albedo Percent Change; 1 indicates head of shiptrack

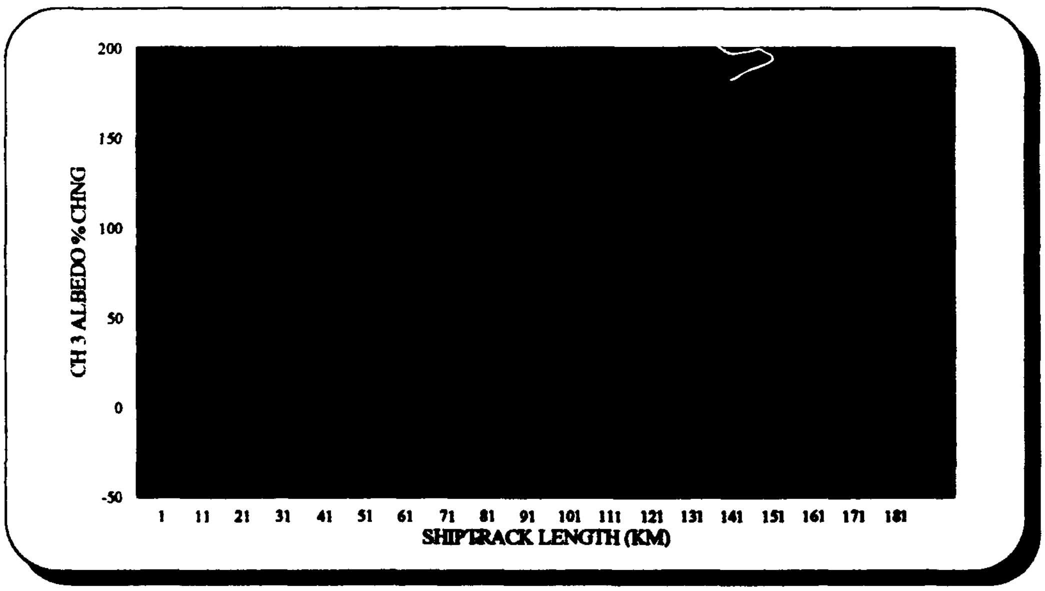

Fig 23. Shiptrack Algorithm Raw Data Plot: represents Arctic Shiptrack Case 1 Channel 3 Albedo Percent Change; 1 indicates head of shiptrack

C. CHANNEL 1 ALBEDO

1. Average Values

Table 4 summarizes the average shiptrack and environment channel 1 albedo values and Figure 24 is a comparison of shiptrack average channel 1 albedos. Subtropic channel one albedo values range from a minimum albedo of 37 to a maximum value of 85. The average albedo for all ten subtropic shiptracks is 59.8 with a standard deviation of 16.7. Arctic channel one albedo values range from a minimum of 15 to a maximum of 50. The average albedo for all nine Arctic shiptracks is 31.2 with a standard deviation of 9.2.

TABLE 4
CHANNEL 1 ALBEDO RESULTS

CASE	ARCTIC ALBEDO	ARCTIC ENVIRONMENT	SUBTROPIC ALBEDO	SUBTROPIC ENVIRONMENT
1	25	21.2	60	60.2
2	15	13.2	49	47.3
3	28	23	40	28.6
4	28	23.2	40	34.7
5	35	34.4	37	34.8
6	40	47.9	80	63.7
7	30	31.6	85	63.8
8	30	24	75	77.4
9	50	59.9	67	67.5
10	N/A	N/A	65	71
AVERAGE	31.2	30.8	59.8	54.9

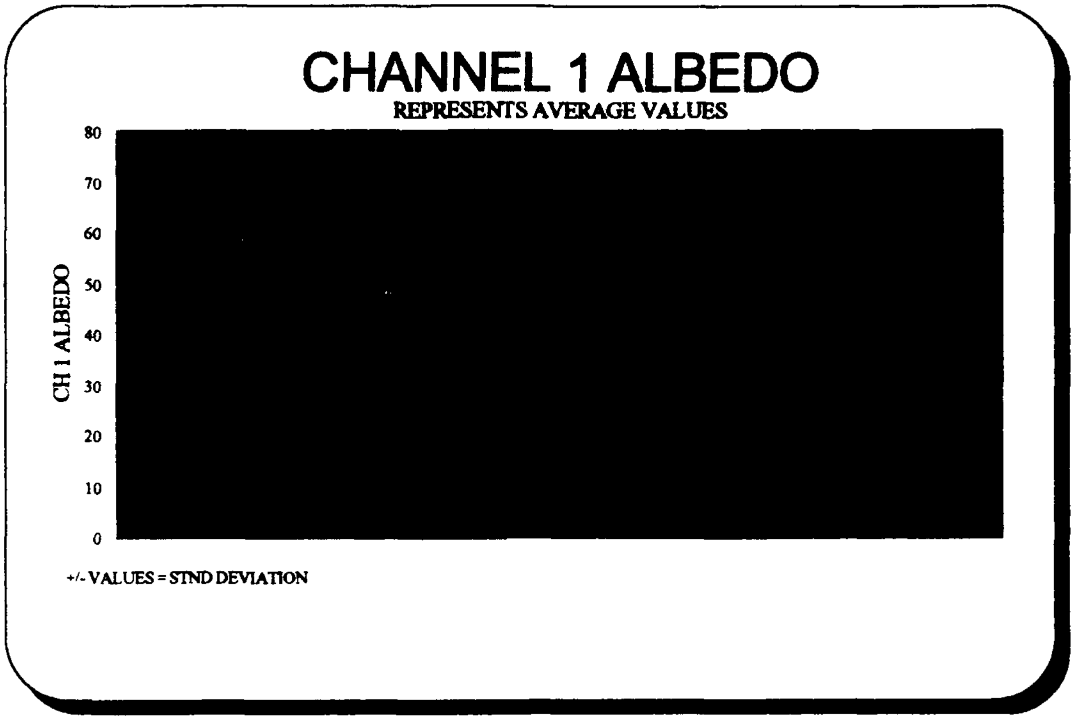

Fig. 24. Average Channel 1 Albedo Values

A comparison between the subtropic and the Arctic channel 1 albedo averages indicates a 91% higher albedo for the subtropic case. Subtropic shiptracks, on the average, vary more in brightness than Arctic shiptracks by 82%. This is consistent with the brighter background stratus clouds in the subtropics.

2. Statistical Significance

The Mann-Whitney (MW) two-sample test (Snedecor and Cochran, 1967) was used to test the significance of the difference of the means of each of the average values. The null hypothesis that the difference between the average values is equal to zero is rejected at the 99% or 95% levels of significance if the Mann-Whitney statistic

gives a probability value less than that for the 99% or 95% values. In this case, the MW test indicates the probability the difference between the channel 1 albedo values is significant and not the result of chance is greater than 99%. This method will be utilized for all significance tests in this paper.

D. CHANNEL 3 ALBEDO

Figure 25 illustrates the average subtropic and Arctic channel 3 albedo values and Table 5 presents the albedo and environment results for each shiptrack case. Subtropic channel 3 albedo values range from a minimum of 4.5 to a maximum of 17. The average subtropic channel 3 albedo is 9.9 with a standard deviation of 3.9. Arctic channel three albedos range from 2 to 15. The average Arctic albedo value is 7.1 with a standard deviation of 3.4.

TABLE 5
CHANNEL 3 ALBEDO RESULTS

CASE	ARCTIC ALBEDO	ARCTIC ENVIRONMENT	SUBTROPIC ALBEDO	SUBTROPIC ENVIRONMENT
1	7.5	5.8	5	3.7
2	5	4.7	9.3	7.9
3	15	9.8	5	3.3
4	9	6.9	4.5	3.7
5	6	4.1	11	9.6
6	8	7.4	17	15.2
7	2	1.3	13	11.3
8	5	1.8	12	10.2
9	6	5.4	12	10.6
10	N/A	N/A	11	10.9
AVERAGE	7.1	5.2	9.9	8.7

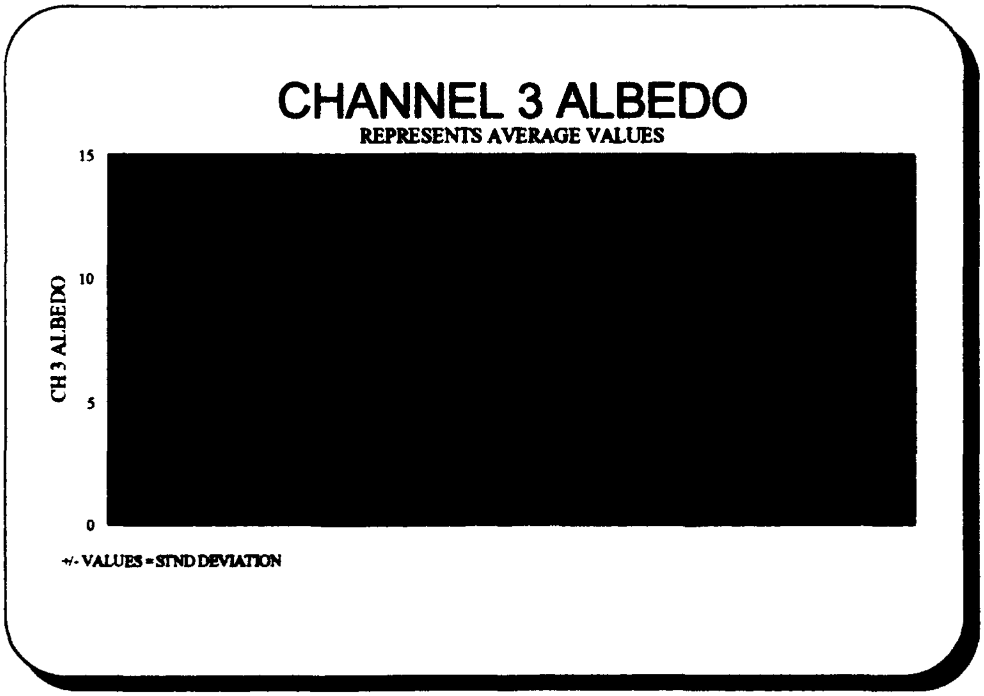

Fig. 25: Average Channel 3 Albedo Values

As was the case with the channel one albedo comparison, the subtropic average channel three albedo is greater than the Arctic average channel three albedo. Furthermore, as was the case with the previous comparison, the subtropic standard deviation is greater than the Arctic standard deviation. In this situation, channel three albedo indicates the level of cloud reflectance as a function droplet size. Thus, for the samples analyzed, it can be concluded the average subtropic shiptrack contains a greater number of smaller droplets than the average Arctic shiptrack and, therefore, is brighter by 20%. Using the MW test, the probability the difference between the average channel 3 albedo values is not due to chance is less than 95%.

E. CHANNEL 4 TEMPERATURE

Table 6 summarizes the shiptrack and environment results for each shiptrack case. Figure 26 depicts the average channel 4 temperature values for each region. Subtropic channel 4 temperatures range from a minimum of 283.2 ^{O}K to a maximum of 290 ^{O}K. The average channel four temperature is 286.4 ^{O}K with a standard deviation of 2.5. The minimum Arctic channel 4 temperature value is 264.5 ^{O}K and the maximum temperature is 276 ^{O}K. The average Arctic channel 4 temperature is 272.1 ^{O}K with a standard deviation of 3.3.

TABLE 6
CHANNEL 4 TEMPERATURE RESULTS
(°K)

CASE	ARCTIC	ARCTIC ENVIRONMENT	SUBTROPIC	SUBTROPIC ENVIRONMENT
1	273.5	273.4	290	289.8
2	272	272.3	290	289.9
3	271.5	271.4	288	285.4
4	276	270.1	288.5	288.2
5	276	276	287	286.9
6	273	272.8	283.2	283.1
7	270	269.4	284.5	284.2
8	272	271.6	284	283.7
9	264.5	264.6	283.5	283.6
10	N/A	N/A	285	285.1
AVG	272.1	272.3	286.4	286.8

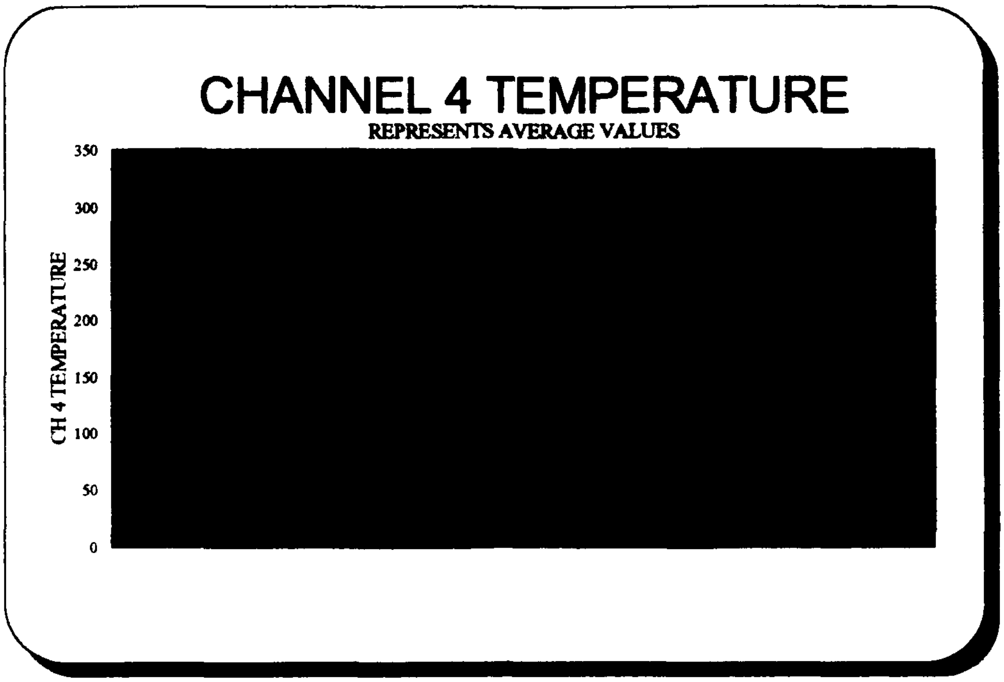

Fig. 26. Average Channel 4 Temperature Values

As expected, Arctic shiptracks are colder than subtropic shiptracks. This is consistent with the much colder environment Arctic shiptracks form in. Furthermore, Arctic shiptracks vary more in temperature than do subtropic shiptracks by 32%. Utilizing the MW test, the probability the difference between the average temperature values are equal to zero is less than 0.01. Thus, the probability the average temperature difference is significant is greater than 99%.

F. CHANNEL 1 ALBEDO PERCENT CHANGE

Table 7 summarizes the channel 1 albedo percent changes between the shiptrack and the surrounding clouds. Figure 27 presents the average channel 1 percent changes for the areas studied. Subtropic channel 1 albedo percent change values range from a

minimum percent change of 55% to a maximum change of 30%. The average albedo percent change for all 10 subtropic shiptracks is 9.6% with a standard deviation of 7.2%. Arctic channel 1 albedo percent change values range from a minimum of 15% to a maximum of 40%.The average albedo percent change for all 9 Arctic shiptracks is 24.4% with a standard deviation of 9.6%.

TABLE 7
CHANNEL 1 ALBEDO PERCENT CHANGE

CASE	ARCTIC ALBEDO PERCENT CHANGE	SUBTROPIC ALBEDO PERCENT CHANGE
1	15	10
2	20	9
3	40	30
4	30	10
5	25	10
6	15	4
7	30	5
8	35	5
9	10	8
10	N/A	5
AVERAGE	24.4	9.6

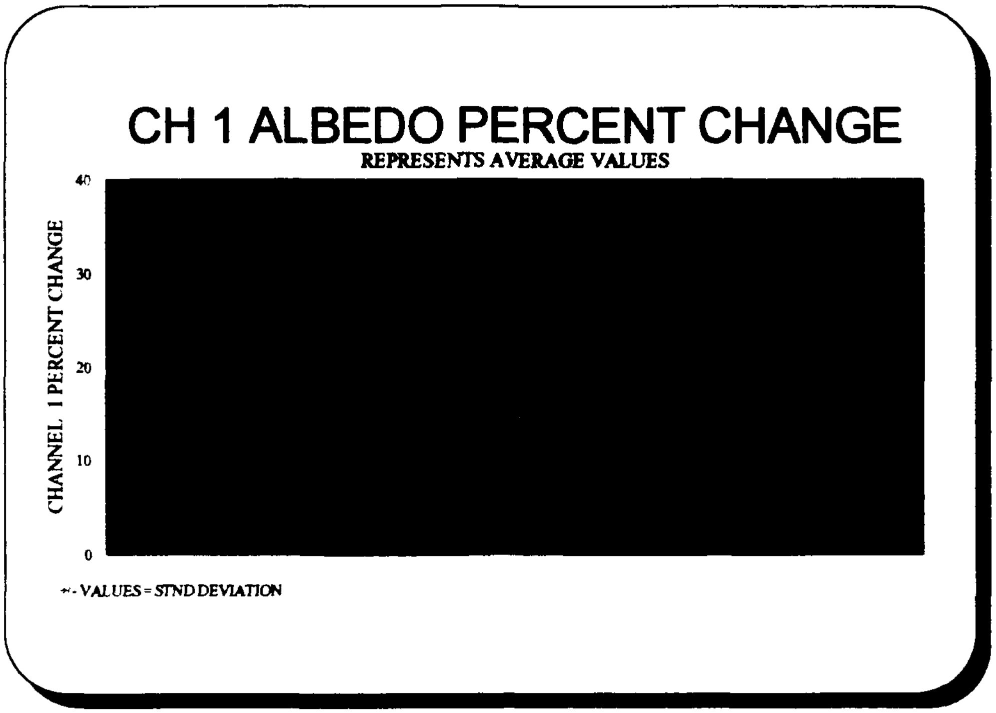

Fig. 27. Average Channel 1 Albedo Percent Change

A large difference exists between Arctic and subtropic channel 1 albedo percent change. Based upon this, it can be concluded Arctic shiptracks tend to be 54% brighter than their environment than are subtropic shiptracks. One potential reason for the difference is the higher susceptibility Arctic clouds have for brightness changes as a result of overall thinner clouds. Statistically, the MW test indicates the probability the difference between the average albedo percent changes is equal to zero is less than 0.05. Thus, the level of significance for the difference between the average albedo percent change values is greater than 95%.

G. CHANNEL 3 ALBEDO PERCENT CHANGE

Table 8 and Figure 28 illustrate the average subtropic and Arctic channel three albedo percent change between the shiptrack and the surrounding cloud. Subtropic channel 3 albedo percent change values range from a minimum of 18% to a maximum of 50%. The average subtropic channel 3 albedo percent change is 23.8% with a standard deviation of 9.6%. Arctic channel three albedo percent changes range from 20% to 80%. The average Arctic value is 38.9 % with a standard deviation of 17.8%.

TABLE 8
CHANNEL 3 ALBEDO PERCENT CHANGE

CASE	ARCTIC ALBEDO PERCENT CHANGE	SUBTROPIC ALBEDO PERCENT CHANGE
1	25	30
2	25	18
3	40	50
4	30	25
5	50	22
6	30	18
7	50	20
8	80	20
9	20	20
10	N/A	15
AVERAGE	38.9	23.8

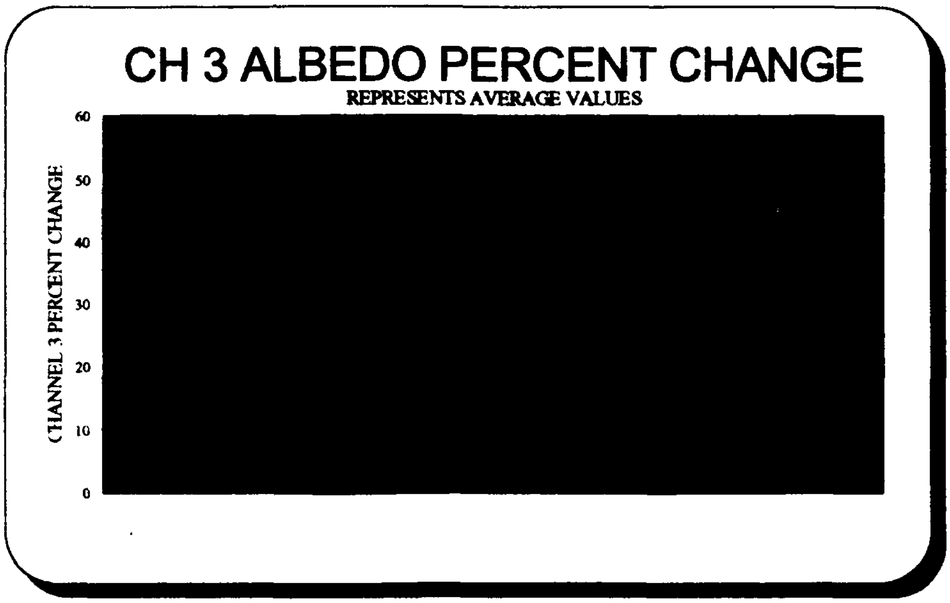

Fig 28. Average Channel 3 Albedo Percent Change

As was the case with the channel one albedo percent change, the average subtropic channel 3 albedo percent change is markedly less than the average Arctic percent change. In this situation, subtropic shiptracks are 63% less bright relative to their environment than are Arctic shiptracks. Furthermore, subtropic shiptrack channel 3 albedo percent changes are 85% less variable than are Arctic channel 3 albedo percent change. While the reasons are uncertain, one possible explanation is Arctic clouds in general have fewer CCN and and a larger droplet size distribution and thus are more susceptible to ship effects than are subtropic clouds. The MW test gives the probability the difference between the average channel 3 albedo percent change values are not equal to zero as less than 95%

H. SHIPTRACK WIDTH

Table 9 summarizes the width results for each region and Figure 29 plots the average shiptrack width for the cases studied. Subtropic shiptrack widths range from a minimum of 5 km to a maximum value of 10 km. The average width for all 10 subtropic shiptracks is 7.3 km with a standard deviation of 1.7 km Arctic shiptrack widths range from a minimum of 4 km to a maximum of 8 km. The average width for all 9 Arctic shiptracks is 5.4 km with a standard deviation of 1.2 km

TABLE 9
SHIPTRACK WIDTHS (KM)

CASE	ARCTIC SHIPTRACK WIDTH	SUBTROPIC SHIPTRACK WIDTH
1	6	7
2	6	9
3	8	10
4	5	9
5	6	6
6	5	5
7	4	7
8	5	5
9	4	9
10	N/A	6
AVERAGE	5.4	7.3

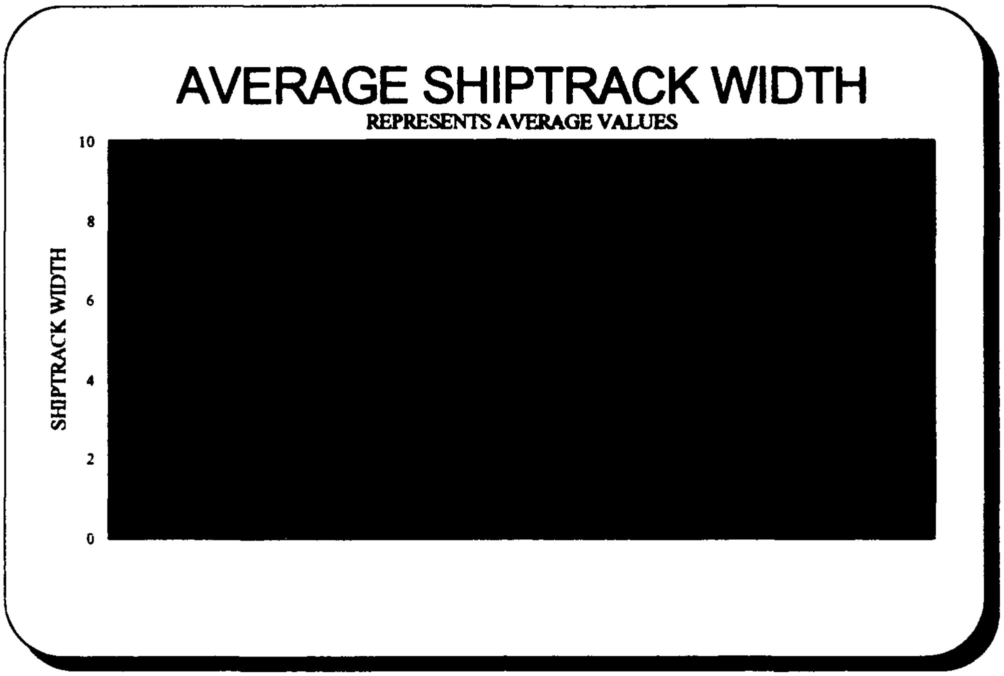

Fig. 29. Average Regional Shiptrack Widths

Based upon the analyzed data, it can be concluded subtropic shiptracks tend to be wider than Arctic shiptracks. One cause for wider subtropic shiptracks lies in the deeper subtropic boundary layer. Here, the formation of larger eddies produces greater mixing which increases the dissipation rate of the shiptrack. The MW test gives the probability the width difference is equal to zero as greater than 0.05. Thus, the probability the difference is not due to chance is less than 95%.

I. SHIPTRACK LENGTH

Table 10 summarizes the shiptrack length results for each region. The average shiptrack lengths for each region are plotted in Figure 30. Subtropic shiptrack lengths range from a minimum of 74 km to a maximum value of 179 km. The average length for all 10 subtropic shiptracks is 133.2 km with a standard deviation of 38.4 km. Arctic shiptrack lengths range from a minimum of 54 km to a maximum of 189 km. The average length for all 9 Arctic shiptracks is 114 km with a standard deviation of 35 km.

TABLE 10
SHIPTRACK LENGTHS (KM)

CASE	ARCTIC SHIPTRACK LENGTH	SUBTROPIC SHIPTRACK LENGTH
1	189	148
2	54	179
3	77	176
4	108	144
5	130	74
6	135	80
7	104	98
8	133	148
9	96	107
10	N/A	178
AVERAGE	114	133.2

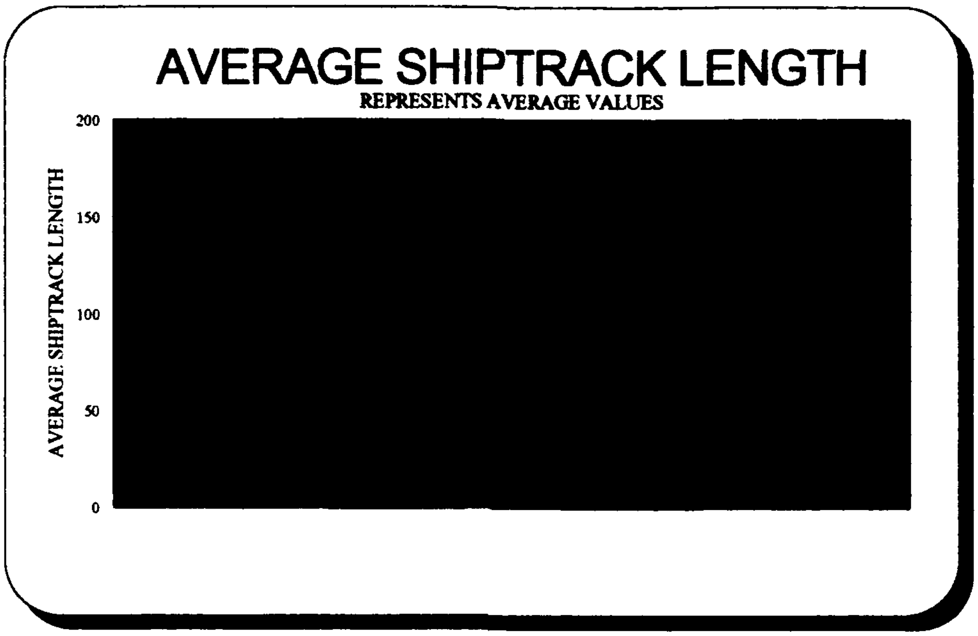

Fig. 30. Average Regional Shiptrack Lengths

Based upon the detection capability of the algorithm, subtropic shiptracks tend to be longer than Arctic shiptracks. One possible reason subtropic shiptracks tend to last longer is because subtropic stratus regions are larger and more homogeneous than Arctic stratus regions. Statistically, the MW test gives the probability the difference between the average lengths is significant and not by chance as less than 95%.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The goal of this thesis was to compare the radiative and physical characteristics of subtropic and Arctic shiptracks using satellite observations. In particular, this thesis was dedicated to the determination of average shiptrack characteristics and trends within regions of environmental extremes. The results point out clear differences between the shiptrack groups studied and these are summarized below.

- Subtropic shiptracks tend to be brighter than Arctic shiptracks in both visible (91% brighter) and infrared (20% brighter) wavelengths.
- Arctic shiptracks tend to be brighter than their environment compared to subtropic shiptracks in both visible (54% brighter) and infrared (85% brighter) wavelengths.
- Subtropic shiptrack radiative characteristics are consistent with consisting of smaller droplets than in Arctic shiptrack clouds.
- Subtropic shiptracks tend to be 17% longer and 35% wider than Arctic shiptracks.

Table 11 summarizes the average albedo, temperature, percent change, width, length, and statistical results.

TABLE 11
SUMMARY OF AVERAGE AND STATISTICAL VALUES

	Arctic	Subtropic	Probability Mean Differences Are = 0
Channel 1 Albedo	31.2	59.8	>99%
Channel 3 Albedo	7.1	9.9	<95%
Channel 4 Temperature	272.1° K	286.4° K	>99%
Channel 1 Albedo Percent Change	24.4	9.6	>95%
Channel 3 Albedo Percent Change	38.9	23.8	<95%
Width	5.4 KM	7.3 KM	<95%
Length	114 KM	133.2 KM	<95%

B. RECOMMENDATIONS

This thesis lays the foundation for future study. These results represent an early description of the radiative and physical characteristics of shiptracks. Clearly, much work is needed before a complete understanding of both Arctic and subtropic shiptracks is possible. Specifically, the following recommendations are suggested:

- Continue current research on the shiptrack detection algorithm. Specifically, improve the algorithm's resolution to enable the detection of a greater number of whole shiptracks and not merely sections of a track.

- Increase in-situ measurements of shiptracks, particularly in Arctic regions. This not only will support current findings but also enhance current shiptrack understanding.

- Continue current research on the correlation between shiptracks and potential ships which produce them. This will determine whether different ships produce different track characteristics.

- Continue to explore the potential use of shiptracks for the detection of naval forces as well as a counter to drug trafficking and illegal fishing.

A better understanding of shiptrack cloud development will aid in our analysis of the marine boundary layer and its modifications by ship activity.

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